Effect of expiratory resistive loading on the noninvasive tension-time index in COPD

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Received 30 June 1999; accepted in final form 22 June 2000

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chronic obstructive pulmonary disease; fatigue; mouth occlusion pressure

Pursed-lip breathing (PLB) is a technique used by some patients with chronic obstructive pulmonary disease (COPD) as a means of decreasing dyspnea. PLB provides a variable expiratory flow resistive load (ERL) imposed by the subject. Whereas ERL with a fixed resistor and PLB are not equivalent in their effects on breathing pattern, they do induce comparable respiratory muscle recruitment responses (29), making it useful to review both techniques together.

The impact of PLB and ERL on the diaphragmatic tension-time index (TTdi) and other parameters in COPD and normal subjects has been studied with conflicting results (6, 11, 15, 21, 22, 29, 30). The TTdi was introduced by Bellemare and Grassino (3) as a means of identifying the fatigue threshold of the dia-
TT_mus to study the effect of ERL on inspiratory muscle performance in COPD patients.

METHODS

Subjects. Patients with COPD were recruited from our pulmonary clinics in the outpatient department of the Boise Veterans Affairs Medical Center. The diagnosis of COPD was made based on history of smoking, medical history, chest X-ray, physical examination, and chronic airflow obstruction as defined by a forced expiratory volume in 1 s (FEV₁) ≤60% of the predicted normal value. Additionally, normal male volunteers with no history of smoking or lung disease took part in the investigation. After the study protocol was explained to all subjects, subjects gave verbal and written consent to participate in the protocol. The study protocol was approved by the Human Subjects Committee of the University of Washington and Research and Development Committee of the Boise Veterans Affairs Medical Center.

Apparatus for application of ERL. The apparatus that was used to apply ERL (Fig. 1) consisted of a mouthpiece attached to a T piece with one-way flap valves such that air was inspired through one port and exhaled through the other port. An airflow resistor was placed in-line at the expiratory limb of the T piece, and both the inspiratory and expiratory limbs of the T piece were attached to a pneumotachometer. The pressure-flow characteristics of the airflow resistor are displayed in Fig. 2. The partial pressure of end-tidal carbon dioxide (PETCO₂) was measured near the pneumotachometer with an infrared Datex CO₂ analyzer (standard equipment on the MedGraphics critical care management module). All measurements were taken with and without the expiratory flow resistor in place. The order of testing with or without the resistor was alternated from subject to subject, and the subjects were not aware of what measurements were being taken until after the testing procedure.

Instrumentation and measurements. Spirometry was performed according to established guidelines of the American Thoracic Society (1) using a SensorMedics 2200 spirometer (SensorMedics, Yorba Linda, CA). This included measurements of FEV₁ and forced vital capacity (FVC). During each session, a minimum of two forced flow-volume loops of reproducible quality was obtained. If the FEV₁ and FVC values

Fig. 1. Experimental apparatus used to apply expiratory resistive loading. See METHODS for complete description. Pneumotach, pneumotachometer.
were not within 5% or 0.100 liter of one another, one additional measurement was taken. The flow-volume loop with the best FEV₁ and FVC was used.

FRC with and without ERL was measured by nitrogen washout in all normal volunteers with the SensorMedics 2200 spirometer. To measure the FRC with ERL, the airflow resistor was placed on the expiratory port of the SensorMedics 2200 spirometer while we waited for the subject to reach a steady-state FRC and throughout the nitrogen washout period. In six of the normal subjects and in all COPD patients, a Gould 2800 body plethysmograph (SensorMedics) was used to measure FRC with and without ERL. In this case, the airflow resistor was attached to a one-way valve, which was, in turn, connected to the breathing valve of the body plethysmograph such that the subject could inspire normally through the breathing valve but exhale through the resistor. The subject was allowed to breathe on this apparatus until steady-state FRC was attained, and subsequently the shutter was closed, allowing measurement of FRC by the pressure plethysmography technique. All airflow and FRC measurements were performed with the subject in the sitting position and were compared with normal predicted values (19).

Airway pressures, P₀₁, and inspiratory and expiratory flows were measured with the MedGraphics respiratory pressure module (RPM) (Medical Graphics, St. Paul, MN). The triple screen pneumotachometer and the pressure transducer (Valdyne) were calibrated according to the manufacturer’s specifications. All measurements were taken with the subjects in the sitting position. Subjects breathed through the apparatus (Fig. 1), which included a pneumotachometer for measuring inspiratory and expiratory airflow along with a port at the mouthpiece for simultaneously monitoring the airway pressures. Subjects were asked to breathe at the rate and depth that was most comfortable to them and such that they could maintain the breathing pattern for at least 10–15 min. After steady state was attained in −5 min, Ti, expiratory times (Te), Tr, and flow rates were recorded. At steady state, the RPM automatically occluded the balloon shutter valve at the inspiratory port during the expiratory phase of a breath. This would occur randomly on every fifth to eighth respiratory cycle. The balloon shutter valve remained occluded for 200 ms into the inspiratory phase, during which time the P₀₁ was measured.

After steady state and a uniform breathing pattern were attained, the Ti, Te, and Tr recorded for each of the P₀₁ measurements were taken as the mean values for the four breaths preceding the occlusion. The tidal volumes (Vₜ) of the four breaths preceding the occlusion were calculated by electronic integration of the expiratory flows over time, and the mean was used as the Vₜ for that occlusion. Similarly, the respiratory rate (RR) was calculated as the average frequency in cycles per minute of the four breaths preceding the occlusion. The minute ventilation (Vₑ) for any given occlusion trial was taken as the product of Vₜ and RR.

For each subject, 10 P₀₁ measurements were taken, and the resultant RR, Vₜ, Vₑ, Ti, Te, and Tr were calculated. The mean values of these measurements were used for each subject.

The Pmax at FRC was measured with the MedGraphics RPM as well. Subjects breathed comfortably on the experimental apparatus without the airflow resistor in place. After a steady-state FRC was attained, the inspiratory and expiratory ports were occluded at end exhalation with a balloon shutter valve, and the subject was asked to perform a maximal inspiratory effort. The shutter valve opened automatically after 5 s, and the highest inspiratory pressure that was sustained for at least 1 s was taken as the Pmax. To reduce the variability that resulted from technique, the measurement was repeated three times, and the mean of the three measurements was considered to be the subject’s Pmax at FRC.

The hemoglobin saturation (SaO₂) of the COPD patients was measured with an Ohmeda Biox 3700 oximeter (Ohmeda, Boulder, CO) while they breathed on the MedGraphics RPM apparatus. The mean of the saturations recorded at the time of each P₀₁ measurement was taken as the SaO₂ for that trial. For each of the COPD patients, the PetCO₂ was measured through a port at the mouthpiece (Fig. 1). The mean PetCO₂ for the four breaths preceding each P₀₁ measurement was taken as the PetCO₂ for that P₀₁ value. The mean of the PetCO₂ values for each of the 10 P₀₁ determinations was used to characterize each COPD patient.

Calculations. According to the method of Gaultier et al. (11), we estimated the Pet as Pet = 5·8 · P₀₁ · Ti. In doing so, it was assumed that inspiratory pressure rises linearly from time 0 to Ti. Therefore, this equation can be rewritten as Pet = 0.5 · k · Ti, where k = 10/s · P₀₁. Subsequently, T₉₉₅ was calculated as T₉₉₅ = P/Pmax · Ti/Ti (25).

Statistical analysis. Means, SDs, and Student’s unpaired t-test were used to describe and compare the baseline data, as well as the measured ventilatory parameters, for the COPD patients and normal volunteers. Means, SEs, and paired t-tests were used to compare the measured values with and without the ERL in both the normal subjects and COPD patients. Paired t-tests were also used to compare the FRC values of the normal subjects, who had the measurements done by both nitrogen washout and plethysmography. All data were analyzed with a database and statistical package (SigmaStat, Jandel Scientific, San Rafael, CA).

RESULTS

Subjects. One female and 13 male patients with COPD were recruited for the study and gave informed consent (Table 1). In addition, 10 normal male volunteers were studied. The COPD group differed from the normal subjects in that they were significantly older (age range 56–80 yr old for the COPD group and 21–49 yr old for the normal subjects), had a history of smoking [61 ± 18 (SD) yr], had marked airflow obstruction

Fig. 2. Pressure-flow characteristics of the airflow resistor used to provide expiratory resistive loading. ○, pressures measured at given flows.
Table 1. Baseline characteristics of COPD and normal subjects

<table>
<thead>
<tr>
<th></th>
<th>COPD Patients</th>
<th>Normal Subjects</th>
</tr>
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<tbody>
<tr>
<td>n</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>Age, yr</td>
<td>73 ± 6</td>
<td>32 ± 8</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>13/1</td>
<td>10/0</td>
</tr>
<tr>
<td>PImax, cmH2O</td>
<td>46 ± 15</td>
<td>106 ± 23</td>
</tr>
<tr>
<td>FEV1, liters</td>
<td>0.80 ± 0.26</td>
<td></td>
</tr>
<tr>
<td>FVC, liters</td>
<td>3.09 ± 0.74</td>
<td></td>
</tr>
<tr>
<td>FEV1/FVC</td>
<td>0.27 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>Smoking, pack yr</td>
<td>61 ± 18</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. COPD, chronic obstructive pulmonary disease; M, male; F, female; PImax, maximal inspiratory pressure at functional residual capacity (FRC), FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; FEV1/FVC, ratio of FEV1 to FVC. *P < 0.001 for COPD vs. normal subjects.

with a mean FEV1 of 0.97 ± 0.59 (SD) liter, and had a significantly lower PImax.

TTmus. The effect of ERL on TTmus in COPD patients is demonstrated in Table 2. Specifically, TTmus decreased by 12% (P = 0.02) with ERL. Whereas most subjects had a drop in TTmus, there was some variability, and some actually had an increase in TTmus with ERL (Fig. 3). Figure 3 also demonstrates the TTmus isolettes of 0.27 and 0.33, which, in validation studies (24), correlate with Bellemare and Grassino’s critical TTdi of 0.12 for COPD patients (5) and 0.15 for normal subjects (3). These critical values represent the fatigue thresholds above which subjects cannot persistently maintain their breathing pattern. Several of the COPD patients were breathing near or above the fatigue threshold at baseline, and in general ERL tended to move these subjects to a more favorable TTmus. The drop in TTmus was the result of a prolongation of TE and a reduction in TI/TT. Otherwise, TI, P0.1, and PI did not change with ERL (Table 2).

Table 2. Ventilatory parameters with and without ERL in COPD and normal subjects

<table>
<thead>
<tr>
<th></th>
<th>COPD Patients (n = 14)</th>
<th>Normal Subjects (n = 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NERL</td>
<td>ERL</td>
</tr>
<tr>
<td>TTmus</td>
<td>0.211 ± 0.019$</td>
<td>0.185 ± 0.018*§</td>
</tr>
<tr>
<td>Tt, s</td>
<td>1.5 ± 0.1</td>
<td>1.6 ± 0.2</td>
</tr>
<tr>
<td>Te, s</td>
<td>2.8 ± 0.2</td>
<td>3.7 ± 0.2†</td>
</tr>
<tr>
<td>TT, s</td>
<td>4.3 ± 0.3</td>
<td>5.3 ± 0.5†</td>
</tr>
<tr>
<td>Ti/Tt</td>
<td>0.35 ± 0.01</td>
<td>0.30 ± 0.01†</td>
</tr>
<tr>
<td>PEi, cmH2O</td>
<td>3.7 ± 0.3</td>
<td>3.8 ± 0.3</td>
</tr>
<tr>
<td>Pi, cmH2O</td>
<td>26.1 ± 1.6</td>
<td>26.7 ± 1.6</td>
</tr>
<tr>
<td>Pi/Pi max</td>
<td>0.61 ± 0.06§</td>
<td>0.62 ± 0.05$</td>
</tr>
<tr>
<td>RR, cycles/min</td>
<td>15.5 ± 1.0</td>
<td>13.3 ± 1.2†</td>
</tr>
<tr>
<td>VT, liters</td>
<td>0.97 ± 0.06</td>
<td>1.04 ± 0.08*</td>
</tr>
<tr>
<td>VE, l/min</td>
<td>14.4 ± 0.7†</td>
<td>12.8 ± 0.8†</td>
</tr>
<tr>
<td>VTi/Tt, l/s</td>
<td>0.66 ± 0.04§</td>
<td>0.70 ± 0.05</td>
</tr>
<tr>
<td>FRC, liters</td>
<td>6.64 ± 0.37§</td>
<td>6.67 ± 0.38$</td>
</tr>
<tr>
<td>SaO2, %</td>
<td>92.1 ± 0.8</td>
<td>92.3 ± 0.8</td>
</tr>
<tr>
<td>PetCO2, Torr</td>
<td>27.5 ± 1.6</td>
<td>27.9 ± 1.6</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of subjects. NERL, no expiratory resistive loading; ERL, expiratory resistive loading; TTmus, noninvasive tension-time index of the inspiratory muscles; Ti, inspiratory time; Te, expiratory time; Tt, total respiratory cycle time; VT, tidal volume; VE, minute ventilation; VTi/Tt, mean average inspiratory flow; SaO2, hemoglobin saturation; PetCO2, partial pressure of end-tidal carbon dioxide. *P < 0.05 for NERL vs. ERL; †P ≤ 0.001 for NERL vs. ERL; ‡P < 0.05 for COPD vs. normal subjects; §P < 0.001 for COPD vs. normal subjects.

In normal subjects, the mean TTmus similarly decreased by 15% (P = 0.03) with considerable variability among subjects (Fig. 4). None of the normal subjects was close to the fatigue threshold (TTmus = 0.33). Again, TE was significantly prolonged, whereas Ti remained unchanged. However, in contrast to the COPD patients, P0.1 and PI were significantly elevated by ERL (Table 2).

The baseline TTmus in normal subjects was 56% less than that in COPD patients (P < 0.001) as a result of a higher PImax in normal subjects (P < 0.001). The other components that factor into the baseline TTmus (Ti, Tr, Pi) were not significantly different between the two groups (Table 2).
Breathing pattern. ERL decreased RR and $V_{E}$ while raising $V_t$ in COPD patients. However, it had no significant effect on these parameters in normal subjects (Table 2). Whereas $V_t$ went up slightly and $T_i$ remained unchanged with ERL, the mean average inspiratory flow ($V_t/T_i$) for the COPD patients showed a tendency to rise but did not meet statistical significance ($0.66 \pm 0.04$ without ERL, $0.70 \pm 0.05$ with ERL, $P = 0.12$). Given the number of subjects studied, the SD of the $V_t/T_i$ values seen, and the observed difference of 0.04 l/s, the power of this test was only 0.36, raising the possibility that a significant difference in $V_t/T_i$ could have been missed.

$P_{0.1}$ and $P_t$. $P_{0.1}$ and its corresponding $P_t$ were unchanged by ERL in the COPD patients. In contrast, $P_{0.1}$ increased by 33% ($P = 0.01$) and $P_t$ increased by 17% ($P = 0.04$) in the normal volunteers. The difference between the $P_t$ values for COPD and normal subjects was not significant. However, when the $P_t$ is considered, there is a marked difference between the $P_t/P_{t_{\text{max}}}$ values of the two groups ($P < 0.001$).

FRC. FRC was significantly larger in the COPD patients compared with the normal subjects ($P < 0.001$). In response to ERL, the FRC remained constant in COPD patients, whereas it increased in normal subjects ($P < 0.05$) (Table 2). This increase in normal subjects was seen when FRC was measured by nitrogen washout in all normal subjects (Table 2) and when it was measured by plethysmography in 6 of 10 normal subjects ($3.45 \pm 0.45$ liters without ERL, $4.07 \pm 0.46$ liters with ERL, $P < 0.001$). The FRC measurements done by both plethysmography and nitrogen washout in six of the normal subjects were not significantly different from each other ($3.36 \pm 0.43$ liters by nitrogen washout, $3.45 \pm 0.45$ liters by plethysmography, $P = 0.52$).

Gas exchange. Peripheral oximetry ($S_aO_2$) was monitored only in the COPD patients and remained unchanged with ERL. $P_{ETCO_2}$ measured in these patients also did not significantly change with ERL.

**DISCUSSION**

In this study, we found that ERL in COPD patients and normal subjects reduces the noninvasive $TT_{\text{mus}}$.

The baseline indexes obtained without ERL are similar to those found in the validation studies done in normal subjects and COPD patients (24). Ramonatxo et al. (25) also used the technique to demonstrate the absence of any difference in $TT_{\text{mus}}$ with and without ERL in normal subjects exercising at 40% of their maximum $O_2$ consumption. However, this is the first use of this method to ascertain the effect of ERL in COPD patients. These noninvasive measurements are similar to Breslin’s (6) more invasive measurements of $TT_{\text{di}}$ in COPD patients using PLB techniques. However, because the $TT_{\text{mus}}$ does not require the placement of esophageal and gastric balloons, it is a technique that may better lend itself to the study of subjects with more severe, acute airflow obstruction.

When comparisons are made between $TT_{\text{mus}}$ and $TT_{\text{di}}$, the issue of whether or not one is better than the other must be raised. In fact, Spahija and Grassino (29) looked at the effect of ERL on the $TT_{\text{di}}$ of normal subjects and found that the $TT_{\text{di}}$ remains unchanged, a result that would appear to be different than our finding of a decline in $TT_{\text{mus}}$ in normal subjects. Alternatively, the two indexes may better be thought of as measurements of two different muscle groups. The $TT_{\text{di}}$ is an index of diaphragmatic function, whereas $TT_{\text{mus}}$ is a better indicator of the output of all inspiratory muscles. Thus, a drop in $TT_{\text{mus}}$ without a significant change in $TT_{\text{di}}$ in normal subjects treated with ERL may be an indication of improved efficiency of the rib cage muscles without a concomitant improvement in the diaphragmatic efficiency. Others have shown that rib cage muscles and diaphragm function can be partially uncoupled and have concluded that the two muscle groups can be fatigued independently, depending on inspiratory recruitment patterns (10, 35). Martinez et al. (18) have also shown that the pattern of ventilatory recruitment in COPD is one of rib cage inspiratory muscle rather than diaphragmatic predominance, thus leading some (24) to suggest $TT_{\text{mus}}$ rather than $TT_{\text{di}}$ as the better indicator of inspiratory muscle fatigue in COPD patients. $TT_{\text{mus}}$ may actually be much closer to the rib cage tension-time index (35) with similar fatigue thresholds (24).

The validity of $TT_{\text{mus}}$ as a measure of respiratory muscle function rests, in large part, on the assumption that $P_{0.1}$ provides an accurate assessment of $P_t$ (11). The calculation of $P_t$ from $P_{0.1}$ assumes a linear rise in respiratory muscle pressure from initiation to termination of inspiration. This is not always the case, and, at least in anesthetized animals and humans, the slope of the inspiratory pressure curve of the occluded airway is often not linear (28, 33, 34). This is especially true at higher RRs. However, whereas the shape of the occluded airway pressure curve is quite variable from subject to subject, the shape of the waveform within any given human or animal subject is quite repeatable (28, 34). Thus, whereas comparisons of repeated mea-
measurements of $P_{0.1}$, $P_t$, and $TT_{\text{mus}}$ for any one individual should be reliable, the use of the absolute values to compare different subjects may be somewhat limited. Alternatively, the validation studies of Ramonatxo and colleagues (24) show a significant correlation between $TT_{\text{mus}}$ and $TT_{di}$ and various respiratory pressure measurements in both COPD and normal subjects, suggesting that use of $TT_{\text{mus}}$ to compare different groups and individuals is indeed valid. This should allow the use of this noninvasive tension-time index to assess the effect of various disease states and experimental protocols on the respiratory muscles. The fact that $TT_{\text{mus}}$ measurements do not require placement of esophageal and gastric balloons makes this technique a much easier tool for assessing subjects who are experiencing acute exacerbation of their respiratory disease and may not tolerate more invasive measurements. As with any other index of respiratory muscle function, it does have its limitations, and the effect on $P_{0.1}$ of various disease states, exercise, medications, ERL, FRC, and other factors must always be considered when evaluating $TT_{\text{mus}}$ values (33).

The tension-time indexes have been used in large part as a predictor of endurance and fatigue in individual muscles or groups of muscles, especially the diaphragm (3, 4, 10). Specifically, the higher the index, especially if near the threshold values, the closer the muscle group is to fatigue. However, it may be more useful to look at the individual components of $TT_{\text{mus}}$ to better understand the effect of ERL on inspiratory muscle function.

Analysis of these components that comprise the $TT_{\text{mus}}$ shows that baseline $TT_{\text{mus}}$ for COPD patients is significantly higher than that for normal subjects because of the marked difference in $P_{t_{\text{max}}}$. In fact, the differences between baseline $T_t$, $T_r$, and $P_t$ are not statistically significant. Similar findings have been demonstrated when $TT_{\text{mus}}$ and $TT_{di}$ in COPD patients have been analyzed (5, 24). When looking at the effect of ERL on the components of $TT_{\text{mus}}$, it is easily seen that there is a reduction of $TT_{\text{mus}}$ in COPD patients only because $T_e$ and $T_r$ are prolonged, whereas the other components remain unchanged. Breslin (6) found that PLB had a similar effect on $T_r/T_t$ without changing $P_{di}$ in those with COPD. In contrast, ERL in normal subjects resulted in not only a prolonged $T_e$ but also an elevation in $P_{0.1}$ and $P_t$. This elevation in $P_{0.1}$ and $P_t$ with ERL has been found by others (13, 25) and significantly minimizes the reduction in $TT_{\text{mus}}$ seen with ERL in normal subjects. To our knowledge, this is the first time that this contrast between COPD and normal subjects in their response to ERL has been noted. It provides a potential explanation of why PLB is commonly used by some COPD patients and not by those without any lung disease. It should also be noted that the difference in response to ERL between COPD and normal subjects in this study may in part be due to the significant difference in the ages of the two groups.

RR, $V_t$, and $V_e$ are also affected by ERL in COPD patients. The decline in RR and $V_e$ and the larger $V_t$ with ERL and PLB have been described by others (6, 30). Reports of the effect of ERL and PLB on these parameters in normal subjects have been mixed (13, 22, 23, 25, 29). Whereas we found similar trends in RR, $V_t$, and $V_e$, none of the changes with ERL in normal subjects was statistically significant or as dramatic as those seen in COPD patients. Our baseline $V_e$ and $V_t/T_t$ values were higher than those of others (24), which was probably a result of the dead space in the experimental apparatus.

It has been shown that a drop in RR without the use of PLB or ERL reproduces many of the same effects as PLB and ERL (20, 30). The braking action of the inspiratory muscles during exhalation probably accounts for a significant slowing of the RR (12, 27), but PLB and ERL may provide an alternative means of slowing the RR without placing additional demands on the inspiratory muscles. This would be most important during the respiratory muscle fatigue, which can be seen with high levels of ventilation (2, 7, 17), and in COPD patients, who demonstrate lower $P_{t_{\text{max}}}$ and higher $TT_{\text{mus}}$ (8). Whereas this study does demonstrate a decrease in RR, $TT_{\text{mus}}$, $V_e$, and $T_t/T_r$ and can, therefore, demonstrate at least some of the potential advantages of PLB and ERL in COPD patients, it does not address inspiratory muscle function during expiration and probably does not fully explain the subjective decrease in dyspnea and objective improvement in gas exchange seen with PLB and ERL. In fact, the greatest decline in workload on the inspiratory muscles may come not from the decline in $T_r/T_t$, RR, and $V_e$ but from their being relieved of their expiratory braking duties. This study also does not address the increased demands placed on the expiratory muscles by ERL. How much ERL is adequate to relieve inspiratory muscle fatigue without inducing expiratory muscle fatigue remains unclear but likely varies dramatically, depending on the subject and breathing conditions.

The determinants of diaphragmatic endurance have been reviewed and include not only the tension-time index but also the work rate and lung volume (9, 16, 32). As discussed above, ERL in COPD patients does indeed decrease the tension-time index and, although not directly measured in our study, may decrease the workload on the inspiratory muscles. The third determinant of inspiratory muscle endurance, namely the volume, was evaluated in our study. FRC did not change with ERL in the COPD patients. This finding was similar to that of Thoman et al. (30), who found no change in FRC with PLB or rate-controlled breathing, but was in contrast to the apparent elevation in FRC with ERL and PLB found by others (15, 23). However, Ingram and Schilder (15) did note that, when those COPD patients who routinely used PLB are compared with those who did not, the PLB group had a much smaller degree of FRC elevation with ERL. Like Ingram and Schilder, we also found significant variability in the FRC response to ERL in COPD patients. Thus different FRC findings may be a result of subject selection. Exactly what accounts for the different FRC
response to ERL remains unclear. It is interesting to note a trend toward worse FEV\textsubscript{1} and/or maximal voluntary ventilation in those who had little to no elevation in FRC in both our study and Ingram and Schilder's study. However, no statistically significant correlation could be found in either of the studies because of the small number of subjects studied. A decrease in end-expiratory alveolar pressure due to the increase in Te would be one potential explanation for a decrease or lack of elevation of FRC with ERL.

As demonstrated by others (15, 25, 29), the mean FRC in the normal subjects did increase significantly. This could contribute to a reduction in the inspiratory muscle endurance (32). In addition, the increase in FRC may in itself decrease the P\textsubscript{a}, thereby decreasing the P\textsubscript{ETCO\textsubscript{2}} and TT\textsubscript{mus}, which otherwise might have been seen with ERL if the FRC had been unchanged in normal subjects. It should also be noted that P\textsubscript{max} was measured only at FRC without ERL. TT\textsubscript{mus} calculated with the P\textsubscript{max} measured at the higher FRC would likely be higher, because P\textsubscript{max} tends to decrease with elevated lung volumes. Thus the TT\textsubscript{mus} in the normal subjects may not have significantly decreased with ERL if the elevated FRC (and therefore reduced P\textsubscript{max}) had been considered.

ERL and PLB have usually been shown to increase arterial P\textsubscript{O}/Sa\textsubscript{O\textsubscript{2}} (6, 20, 26, 31), whereas their effects on arterial P\textsubscript{CO\textsubscript{2}}, P\textsubscript{ETCO\textsubscript{2}} and CO\textsubscript{2} production have been variable (22, 23, 25, 30). Our study failed to show any significant change in either Sa\textsubscript{O\textsubscript{2}} or P\textsubscript{ETCO\textsubscript{2}} with ERL in COPD patients. One potential explanation for this is the increased workload placed on the expiratory muscles with the fixed expiratory resistor. This may have resulted in a higher CO\textsubscript{2} production and O\textsubscript{2} consumption, which, in turn, could have masked any improvement in gas exchange when only Sa\textsubscript{O\textsubscript{2}} and P\textsubscript{ETCO\textsubscript{2}} were measured. The higher dead space of the experimental apparatus may also have affected the P\textsubscript{ETCO\textsubscript{2}}.

In summary, we have demonstrated that ERL results in a decline in the TT\textsubscript{mus} of COPD patients by reducing the T/Tr. It has no effect on the P\textsubscript{ETCO\textsubscript{2}} or the FRC of these patients. This may, in part, explain the use of PLB by these patients. We have also shown that the noninvasive TT\textsubscript{mus} is well tolerated by patients with chronic dyspnea and provides a practical means of studying the tension-time index of these patients at baseline and potentially during acute exacerbation of their chronic disease.

This study was supported in part by the Medical Research Service of the Department of Veterans Affairs.

REFERENCES


